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All Optical Switching Using Optical Fibers and Nonlinear Organic Liquids

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ALL-OPTICAL SWITCHING USING OPTICAL FIBERS AND NONLINEAR ORGANIC LIQUIDS

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ABSTRACT

Nonlinear optical organic liquids based on 2-methyl-4-nitroaniline (MNA)-type molecules in solution are potentially practical as third-order materials, featuring a large and fast intensity dependent index of refraction, high optical loss, insusceptibility to laser damage and a freely adjustable refractive index. The latter property makes them compatible with glass substrate devices, and permits ease of fabrication for demonstration devices. Concepts and preliminary data are presented for a high speed all optical switch based on glass waveguides suspended in a nonlinear liquid cladding of index matched organic solutions.

1. Introduction.

All-optical waveguide devices based on ultrafast third order nonlinear optical properties are desired for a variety of functions including fiber optic switching, digital logic, optical limiting and optical computing systems. Materials potentially useful in these application must possess (a) high third order nonlinearity, (b) ultrafast response time and (c) excellent additional requisite physical properties. These properties include superior transparency, freedom from scattering centers, uniformity, optically flat surfaces, chemical and environmental stability and processibility. Currently a number of inorganic optical materials satisfy these criteria, but no single material has emerged that may be termed as an optical "silicon." Further enhancement of nonlinear properties is still desirable for better performance and in addition, increased flexibility in tailoring the requisite physical properties is crucial. Organic materials are often cited as having the best long range promise for such devices (1), which may exceed efficiency of inorganic materials in many aspects, such as faster response time with a low dielectric constant and higher third order nonlinearity in the materials' transparent regime(2,3). In addition, great flexibility in molecular design and modification, for the enhancement of

properties is easily afforded. In spite of intensive research using organic materials, relatively few working devices have been demonstrated to date due to a variety of problems in selecting, processing and fabricating such materials into appropriate device configurations.

Among organic nonlinear optical (NLO) solids available today, conjugated macromolecular systems such as the polydiacetylene(PDA) family and guest-host systems (in which an NLO material, e.g. MNA, is composited with a highly transparent and chemically and dimensionally stable polymer, e.g. polymethylmethacrylate) seem to be good candidates for the application. However, when these materials are in a solid form, it is not easy to fabricate them into desirable configurations and at the same time match the refractive indices with associated optical elements as may be dictated in a device configuration.

We discuss concepts for a class of switching devices intended to be easy to fabricate and test, based on combining nonlinear organic solutions with glass fiber waveguides. In constructing practical nonlinear waveguide devices for the application discussed above, many characteristics other than large, high speed n_2 effects become important. In particular, low loss (the sum of absorption and scattering) is significant. The effective nonlinear response for many device configurations is not the intensity induced index modulation $n_2 \cdot I$ but the figure of merit, $n_2 \cdot I/\alpha\lambda$, where I is the intensity of the incident beam, α is the loss per cm and λ is the wavelength of the incident beam.

A more mundane and often overlooked factor is that for maximum flexibility in device design it is desirable that a third-order material should have a linear refractive index compatible with the other materials typically used in fiber optics and waveguide structures. For example, some high performance organic films or crystals have indices in the 1.6-1.9 range, making it difficult to integrate them with glass structures of index ≈ 1.45. In addition, laser damage threshold of the nonlinear material under consideration must be high enough to withstand the fields required to generate significant nonlinear effects. Finally, the usefulness of a material is severely limited unless a fabrication technology exists to produce high precision, low loss waveguide forms. Organic materials exist which satisfy each of these requirements, but no one material so far satisfies them all at once. In an attempt to develop approaches to maximize utilization of organic NLO materials and minimize processing and fabrication complexities, we employed NLO materials in solution form.

Solution form of NLO materials provides at least two advantages for research and feasibility demonstrations. First, adjusting the linear refractive index to match a given fiber cladding will be significantly easier than in the solid state. Second, the transparency problem will be drastically reduced since the scattering and inhomogeneity prevailing in most solid films will be avoided. As a tradeoff for these advantages, solutions raise problems such as concentration limits and temperature dependence of the refractive index. Therefore, several solvents must be evaluated to identify the range of refractive index available, and temperature must be controlled as accurately as possible to minimize the temperature dependent changes of refractive index.

With these factors in mind, it is instructive to note that Friberg et. al. (4) were able to demonstrate all-optical switching in a simple dual core optical fiber, operating as a Jensen coupler (5). In their early experiments, the "nonlinear" material was ordinary silica, whose n_2 is only 1/10,000 that of a prototypical high performance polymer such as PDA, in the material's transparent regime (6). Because of the extremely high transparency of silica, however, combined with the existing technology to form long low loss fibers, this small nonlinearity was available over a long optical path length (many cms) in a "pipelined" switching configuration capable of subpicosecond speeds. Switching power threshold was on the order of 1 kW. Using the organic NLO solutions of the present research, larger n_2 effects may yield switching times an order of magnitude faster with optical switching power on the order of 100mW.

2. Dual-Waveguide Switching Device Using Liquid Cladding.

In view of the difficulty of fabricating high precision nonlinear thin film waveguides, it is clearly a practical advantage to work with devices based on glass fibers as an existing high quality waveguiding structure, provided more strongly nonlinear materials can also be introduced. Clark, Andonovic and Culshaw (7) modeled dual waveguide devices in which the nonlinear material in a dual-core optical switch was located contiguous with the cladding, as shown schematically in Figure 1. A directional coupler is first fabricated which, under low power conditions, transfers 100% of the optical power from fiber 1 to fiber 2. Under the control of a separate optical pump beam, or else a simple increase in power of the signal itself, the nonlinear core or cladding index $n = n_0 + n_2 \cdot I$ (where n_0 is the linear refractive index) is modulated sufficiently to alter the coupling ratio between the two fibers. If the coupler length and power threshold are set correctly, this can cause the signal to exit 100% from fiber 1 instead of transferring to fiber 2, effecting an optically controlled switch. This class of devices is denoted nonlinear coherent couplers (NLCC). Figure 2 suggests that a simple NLCC can in principle be made by immersing a rather ordinary bidirectional coupler with etched cladding in an index controlled bath of a nonlinear liquid. Although it is inherently less efficient to locate the active nonlinear material in the cladding than the core, this can be compensated by large n_2 values, long path lengths, and very accurate index control of the nonlinear cladding element. The goal, in developing such a switch, is subpicosecond speed

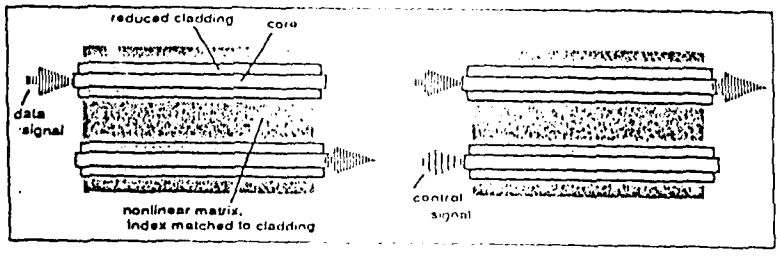

Figure 1. The Nonlinear Coherent Coupler, NLCC

combined with a power threshold for switching on the order available from diode lasers, 10-100mW.

Highly transparent third-order materials whose linear index can be precisely adjusted to match glass cladding values are essentially limited to glasses, doped glasses or liquids. The latter have the advantage of potentially much larger nonresonant nonlinearities. Although liquid CS_2 is a standard for third-order nonlinear optics, relatively little effort has been devoted to developing new, higher performance liquids as practical device materials. Using high concentrations of NLO solutions, it is possible to precisely match the index to a range of desired values. In high concentrations, n_2 values comparable to the best solid organic materials may be possible, along with the low loss and self-healing characteristic of high purity liquids. A number of approaches such as gelation may be adopted to "fix" the solution for transition to a solid device, if desired.

3. Device Model.

The equations describing power transfer within a NLCC were derived by Jensen (5). The NLCC is defined as two parallel waveguides spaced closely enough for evanescent wave overlap and separated by a nonlinear medium. For a coupler with active region equal to the characteristic coupling length, L_c, the coupler will operate in the "crossed state" at low powers (i.e. all of the power launched into one waveguide will exit the second waveguide). As the input power to waveguide 1 is increased, the power out of waveguide 1 is described by

$$P_{out}(1) = P_{in}(1)\ [1 + CN(\pi|(P_{in}(1)/P_c)^2)]/2$$

where CN is a Jacobi elliptic function and

$$P_c = A\ \lambda/L_c\ n_2$$

where n_2 is the nonlinear refractive index of the medium constituting and surrounding the guides and A is the cross-sectional area of each guide. The nonlinear dynamics

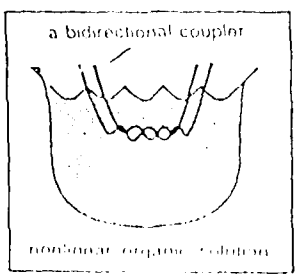

Figure 2. A Simple NLCC with Glass Fibers in a Nonlinear Liquid Bath.

responds to both core and cladding n_2. A goal of this investigation is enhancement of the effective nonlinear index of the medium surrounding the coupler guides by using organic NLO solutions.

Switching of the NLCC from the crossed to the parallel state is shown as a function of input power in Figure 3. The effect of a factor of two increase in the nonlinear index of the medium constituting and surrounding the coupler guides is shown by the two curves; the coupler with the higher nonlinearity shows 100% switching at a lower power. Since some nonlinearity is always present in the core, and the higher field there emphasizes this contribution over that of the cladding, the effect of a nonlinear liquid bath is essentially to enhance the performance (i.e. reduce the power threshold for switching) which is already present due to the small nonlinearity of the glass core.

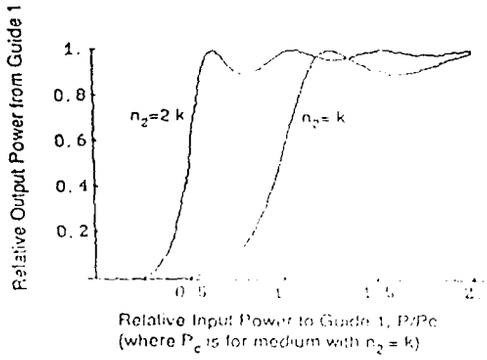

Figure 3. Signal Fraction Exiting Fiber 1 as a Function of Input Power.

4. Organic NLO Materials and their Solvent Systems.

For the preliminary demonstration of all-optical switching using NLO solutions, commercially available 2-methyl-4-nitroaniline (MNA) was selected, which is primarily known as a second order material (2). MNA also possesses considerable third order nonlinear optical properties, whose high speed nonresonant nonlinear index of refraction (n_2 = 25.0 x 10^{-11}esu) is 2-3 times greater than that of Si or p-nitroaniline (3). Exceptionally high solubility of MNA in polar solvents allows a wide range of refractive indices to be available. MNA also provides a wide transparent regime (from mid visible to near infrared) in which optical losses are minimum (Figure 4).

Suitable solvent systems for MNA were identified for the solution based all-optical switching device. Dimethylformamide (DMF), p-dioxane, propylene carbonate (PC) and tetrahydrofuran (THF) provided high solubility with a wide range of index choices. Solubility of MNA in each solvent (HPLC grade) at room temperature was measured for the determination of the range of refractive index available (Table 1).

Table 1. Solubility of MNA in Different Solvents at Room Temperature.

SOLVENT	SOLUBILITY (grams/liter)
DMF	527
p-DIOXANE	261
PC	154
THF	349

Table 2. Temperature Dependence of Refractive Indices of MNA Saturated Solutions.

SOLVENT	REFRACTIVE INDEX	
	15°C	25°C
DMF	1.5660	1.5613
p-DIOXANE	1.4766	1.4725
PC	1.4580	1.4546
THF	1.4854	1.4817

Variation of refractive index of the MNA solution in various solvents at 20°C as a function of concentration was obtained using an Abbe refractometer. Refractive indices available as shown in Figure 5, range from 1.4 to 1.5 with the solvents used, from which one can easily match the refractive index of silica optical fibers. Temperature dependence of refractive index in MNA saturated solutions measured at 15°C and 25°C is tabulated in Table 2. Fluctuation of refractive index as a result of the temperature variation turned out to be approximately 0.0004/°C, so that it is essential to control the solution temperature to better than ±0.1°C in this experiment in order for only electronic nonlinear refractive index change to be effective.

One can tailor the refractive index to the desired value by varying one or more of the following factors; (a) concentration of the NLO solution, (b) temperature of the solution and (c) solvent type. It is true that the higher the number density of the NLO molecules in solution, the larger the nonlinear effects are. In practice, however, not only nonlinearity but also optical loss, solvent volatility, stability of polymeric components in

an Argon-ion laser (515nm) for pump beam were chosen in this research. All-optical switching demonstration using optical fiber couplers with organic nonlinear solutions is in progress.

A large number of organic and polymeric molecular systems have been identified with significantly larger third order nonlinearities compared to MNA. While polymeric solutions with as high concentrations may not be possible to prepare, gels and oligomers may be prepared with large nonlinear coefficients and high number density of the active molecules. A number of organic NLO molecular systems have been designed and synthesized in our laboratory (8), which are expected to possess significantly larger third order nonlinearities. In addition, several of these molecules incorporated diacetylene and acetylene units. Polymerization in these systems may lead to soluble materials with large nonlinear coefficients. Eventually, these polymeric NLO materials are expected to improve the device performance by at least an order of magnitude leading to a switching power threshold of less than 100mW.

5. Preliminary Experiments.

As a preliminary test, we have constructed a device as shown in Figure 2, developed a high precision laboratory method of matching liquid indices to glass cladding, and demonstrated modulation of the probe beam by a pump beam at low speed using thermal effects. This demonstration, which has been carried out with thermal changes in the index of refraction of the surrounding liquids, gives some indication of the dynamics to be expected from electronic nonlinearities of the NLO solutions in subsequent experiments.

A cross-section of the experimental apparatus is shown in Figure 6. The basic coupler is of the fused type and is fabricated from two optical fibers with single mode cutoff at about 590 nm. The fused or "active" region of the coupler is about 1 cm long and has an estimated minimum diameter of about 40 microns. At both ends of the active region, at the points of bifurcation, an epoxy encapsulant is used to anchor and seal the coupler. As shown, after encapsulation, only the active region remains available for

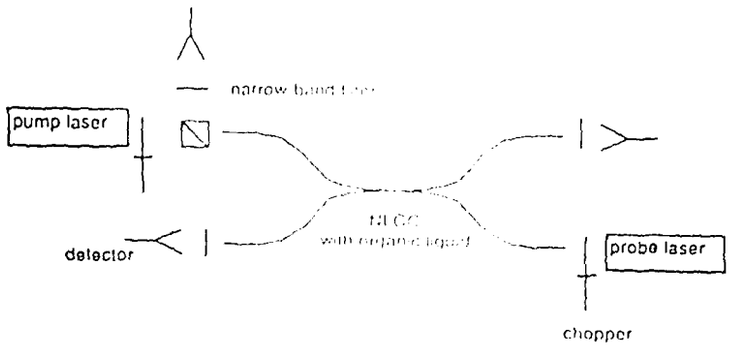

Figure 6. Preliminary Experiment

the device assembly, such as epoxy encapsulant and so on must be taken into consideration. Consequently, non-volatile PC was selected as the best choice as a test solvent for the demonstration in which epoxy encapsulant was found to be very stable for long periods of time.

A UV-VIS transmission spectrum of MNA was obtained to determine the transparent window available for the probe and pump beams. As shown in Figure 4, in MNA solution, excellent transparency is seen for wavelength of 450nm through near infrared with an absorption peak at 380nm. Output from a HeNe laser (633nm) for probe beam and from

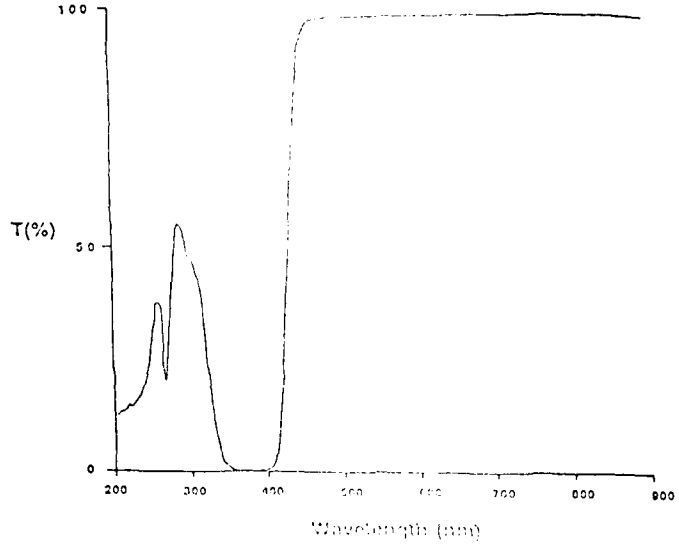

Figure 4. UV-VIS Transmission Spectrum of MNA

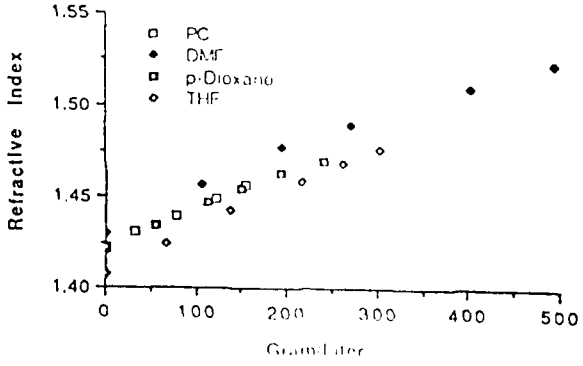

Figure 5. Refractive Indices of MNA Solutions at 20°C.

exposure to the test liquids. The coupler sits within a stainless steel tube, with central section cut out. The tube passes diametrically through a liquid reservoir and serves as a liquid-tight bulkhead through which the input and output fibers at both ends of the coupler pass. As some of the test solvents are highly volatile, the reservoir is fitted with a removable cap to prevent evaporation. The liquids are tested by filling the reservoir until the active region is submersed. The temperature of the chamber may be controlled by heating or cooling through the walls of the reservoir, since temperature control is important to stabilize the splitting ratio. If necessary, the liquid in the reservoir may be stirred with a magnetic bar.

The apparatus may be used with a single laser input beam of adjustable intensity which serves as both the pump beam and the probe beam, or else two lasers operating at different wavelengths may be used to separate the probe/signal and pump/control functions. In our initial tests it was convenient to use separate lasers for the probe and pump beams; the arrangement for launch and detection of transmitted optical signals is shown in Figure 6. The probe beam input to the coupler was stripped of cladding modes by use of index matching fluid applied over the first 3 to 5 cm of uncoated fiber tip.

With separate pump and probe lasers it is easy to maximize the amount of pump beam power which enters into the organic liquid under test. While the probe beam is restricted to single mode operation for proper functioning of the switch, the pump beam is not similarly restricted. Excitation of cladding modes by the pump beam assures that substantial pump power will enter the nonlinear liquid. To further enhance interaction with the liquid, the wavelength of the pump beam may be chosen to lie just below cut-off, where the second mode is loosely bound, or far above cut-off where the fundamental mode is loosely bound. Balancing these advantages, however, is the added complexity that a dual laser arrangement poses. The pump and probe channels must be separated at the detectors by use of, for example, narrowband filters, and/or lock-in detection using modulation frequencies for the two lasers which are not related harmonically.

As a preliminary test of the device apparatus, an argon ion laser (Coherent Innova 90-6) producing 0.5-4 W at 515 nm was used as the pump beam in Figure 6. The distance from the pump launch end to the coupler active region was less than 1 meter. A comparison of coupler pump beam throughput (sum of both output arms) before and after the application of index matching fluid to the active region revealed that 15 % or more of the launched power could be made available for excitation of the organic fluid.

Optical modulation of the HeNe probe beam was demonstrated under control of the argon pump beam, by means of thermal modulation of the active region of the coupler, as shown in Figure 7. This effect was quite slow as expected, on the order of 10 ms, but served to demonstrate principles similar to those which will operate in subpicosecond experiments using purely electronic index modulations. Addition of an index matching fluid to the active region reduced the amplitude of the probe beam modulation, possibly because the liquid stabilized the active region temperature through convective cooling. The frequency response of the probe beam modulation rolled off at only a few kHz, characteristic of a cooling-rate limited system. Note that it is difficult to distinguish

experimentally between the contributions of the core and cladding nonlinearities, whether thermally or electronically induced.

The experimental apparatus is now being readied for high speed all-optical switching experiments using a sub-nanosecond pulsed laser pump in conjunction with the organic NLO liquids as described above. To index match such liquid baths to the cladding or other selected glass references accurately, a scattering technique was developed using a HeNe laser beam directed transversely onto the etched fiber/liquid interface in a test cell. An index match is indicated by titrating the liquid index until the scattered light is minimized. By careful collection of scattered light and use of a micropipette to adjust the solvent mixture, it was possible to match the index to better than 0.0001. The liquids used were mixtures of organic solvents 1,1-diethoxymethane (n=1.42) and acetylene tetrabromide (n=1.48), selected to bracket silica (n=1.4570 at 633 nm). Using improved sensitivity, it is expected that ±0.0001 index control can be achieved, which is sufficiently precise to set the propagation parameters of single mode waveguides.

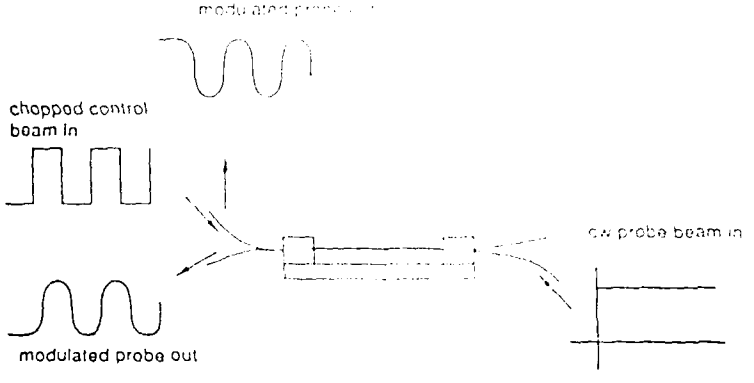

Figure 7. Optical Coupling due to Thermal Index Modulation.

6. Concluding Remarks.

To demonstrate all-optical switching using organic NLO solutions, MNA was selected as a test NLO material and its suitable solvent systems were identified. The range of refractive index available was also obtained from the MNA solutions in various solvents and at different temperatures. The transparent regions in MNA solution was determined for the probe and pump beams employing UV-Vis spectroscopy. A test apparatus has been designed and assembled which enables optical interaction between a fiber optic single mode coupler and NLO liquids. Thermal modulation of an input signal has been demonstrated with this apparatus. Subpicosecond all-optical switching using organic NLO solution (e.g. MNA/PC), including new NLO materials synthesized in our laboratory, is now under investigation for enhanced switching efficiency (faster switching speed, smaller switching power threshold and shorter interaction length).

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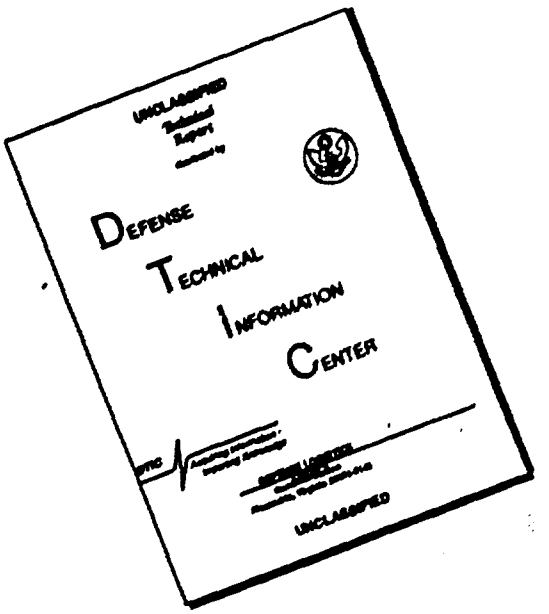

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